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PALEOMAGNETIC CHARACTERISTICS OF THE JURASSIC COMPLEX WITHIN THE SUDUR SHELF ZONE OF THE GREATER CAUCASUS (AZERBAIJAN)

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Summary. The article presents a detailed stratigraphical division of the Jurassic complex of the continental shelf of the North Caucasian margin of the Eurasia. The stratigraphy of Jurassic rocks in this region, which corresponds to the southern margin of the Scythian platform, has not been well studied. On the other hand, paleomagnetic research has never been conducted in this area before. The studied region is located on the northern flank of the southeastern part of the mountain-folded system of the Greater Caucasus. To study the paleomagnetic properties of the Jurassic rocks, 80 oriented samples were collected from the Tahirjalchay section. The magnetic susceptibility and the natural remnant magnetization of deposits vary between 0.6×10^{-3}-1.6×10^{-3} BS and 2.9×10^{-3}-16.9×10^{-3} A/m, respectively. The average value of the permanent component indicates that the magnetization is close to its initial value and can therefore be used to compile a paleomagnetic profile. Based on paleomagnetic data, for the first time, the kinematic parameters of the Jurassic tectonic blocks on the southern margin of the Scythian Platform were studied. Analysis of the research materials reveals the extent of the angular displacement of the block. In the magnetostratigraphic analysis of the Tahirjalchay section, a total of 5 direct magnetization zones and 5 reverse zones were identified. Using these magnetic zones, the boundaries between different stratigraphic units were determined: Aalenian-Bajocian; Bajocian-Bathonian; Bathonian-Callovian; Callovian-Oxfordian; Oxfordian-Kimmeridgian.

Keywords: *Tahirjalchay section, magnetic sensitivity, residual magnetization, paleomagnetism, magnetic polarity*

Introduction

The Greater Caucasus orogenic system forms a morphological barrier along the southern margin of the Scythian Platform. It extends from the southern part of the Caspian Sea to the northern margin of the Eastern Black Sea. It developed during several phases of deformation in Mesozoic-Cenozoic periods. The Jurassic deposits, which are widespread within the Azerbaijani part of the Greater Caucasus, are represented by the middle and upper stages. The Middle Jurassic deposits have nearly identical facies. During the Upper Jurassic period, several basins were formed, differing in sedimentation conditions. Despite the long history of studying the Jurassic rocks of the Southeastern Caucasus, their age dismemberment and stratigraphic correlation cannot be considered complete. A number of uncertainties related to division and subdivision of the Upper Jurassic deposits sill remain there. It is appropriate to solve these issues using paleomagnetic research data. The present paper expounds upon the paleomagnetic research results of the Middle-Upper Jurassic rocks of the Tahirjalchay section (Sudur zone), which are located within the Side range megazone of the Greater Caucasus. The detailed magnetostratigraphic studies were carried out on the basis of paleomagnetic measurements. A detailed age division of the Middle and Upper Jurassic intervals of the northern slope was carried out, and five direct and five reverse magnetized paleomagnetic zones reflecting the change of the poles of the Earth's magnetic field were distinguished. The obtained results will help to complete the magnetostratigraphic scheme of the Middle-Upper Jurassic boundary interval of the Greater Caucasus. An additional comprehensive study of this section was carried out, including sedimentological description and sampling from different levels for paleomagnetic, mineralogical and chemical analysis. The purpose of this study is to clarify the sedimentological zonality and age correlation of the Jurassic successions formations on the northern flange of the Greater Caucasus marginal sea basin in Azerbaijan (Kangarli et al., 2013).

Methods

In the field work conducted in 2015-2022, the detailed study of rocks and layer by layer description of sections was carried out in order to identify genetic signs and separate litogenetical types (Храмов и др., 1982). The oriented samples of paleomagnetic studies were taken every 0.5-1 m. Petromagnetic studies of samples taken from the Tahirjalchay section were carried out in Moscow at the laboratory “Main Geomagnetism and Petromagnetism” Institute of Physics of the Earth RAS. Paleomagnetic studies of the samples included measurements of natural remanent magnetization (J_n), magnetic saturation tests, thermomagnetic analysis, and alternating-field magnetic cleaning, saturation moment of magnetic mineral (Ms), the moment of saturation of remanent magnetization (Mrs), determination of normal magnetization curves Mr (B) and residual coercive force Bsr (destructive field), demagnetization by variable and constant magnetic field and temperature ets. The *K* parameter was measured at a MFK1-FB kappabridge. The dependence of *K* on temperature was studied using a MFK1-FA kappabridge with a CS3 furnace. Alternating- field magnetic cleaning was performed at a LDA-3 AF demagnetizer with measurements of J_n at a JR-6 spin-magnetometer and a cryogenic (SQUID) magnetometer 2G-Enterprises.

Section structure

The Tahirjalchay section is located in the Sudur zone of the Side range structural-formation zone of the Greater Caucasus. The Middle Jurassic is represented by clay-terrigenous rocks, and the Upper Jurassic is represented by gypsum-bearing lagoons and carbonates. The Aalenian-Lower Bajocian interval consists of gray sandstones (25-100 m) interbedded with clayey shales. The shelf facies on the top and the lagoon facies at the bottom represent The Upper Jurassic section. The Tahirjalchay suit, which is composed of a combination of heater yellowish and bluish-green sandy shales interspersed with greenish calcareous sandstones and layers of crystalline limestones and dolomites can be found at the lower section of the Upper Jurassic deposits. This was first described by Isaev (Исаев и др., 1977; Kangarli, Mehdiyeva, 2017). The sediments, which are 50-60 meters thick, are located on top of the Upper Aalenian horizons without any basal conglomerates. The younger geological layers display a more noticeable purple-red hue in the suite, and its summit is permeated by frequent veins of gypsum-anhydrite. Additionally, the Gushgala suite of the Upper Oxfordian gypsum-bearing argillite- arenaceous sediments unconformably covers and overlaps this suite.

The Gushgala Formation exposed on the eastern slope of the eponymous mountain (Fig. 1) has an unconformable relation with the overlying Gukhur Formation, which consists of a continuous sequence of limestone and dolomite rocks. The lower part of the sequence is dominated by grey and dark-grey dolomites; pink dolomite also present. The upper part consists mainly of light-grey to pinky limestone, which is often brecciated, and contains oolitic sandstone (Mehdiyeva, 2022).

The thickness of these successions increases towards the central, most subsided part of the Sudur zone, rising from 20-50 m in the Gushgala mountain area to 450-500 m on the slope of Garagaya Mountain.

Magnetic properties of rocks

Petromagnetic research methods are an independent and promising tool for solving a wide range of issues in geology, geophysics, as well as other geoscience disciplines. The performance of petromagnetic experiments is currently seen as an essential component of paleomagnetic research, necessary for assessing the age of components of natural remanent magnetization recorded within rocks.

The hysteresis curves of samples from the Tahirjalchay section exhibit a paramagnetic character (Fig. 2a), although with a significant increase in the plot, it becomes clear that the upper and lower portions of the curve diverge (Fig. 2b), indicating the presence of minute amounts of ferromagnetic materials in the rocks.

After correction of the paramagnetic susceptibility, the hysteresis loop adopts a ferromagnetic shape, and it becomes clear that the magnetization (Ms) approaches saturation in the magnetic field region of 0.5 Tesla (Fig. 2c).

The curve of normal magnetization (Fig. 2d) shows that after rapid growth in the range of fields 0-0.5 mT, the magnetic moment does not saturate, but continues to grow slowly. This can be considered as a definite indication that in addition to relatively low-coercivity minerals (the presence of which is indicated by B_{CR} values in the region of 400 mT); the ferromagnetic fraction of rocks also contains highly coercive minerals.

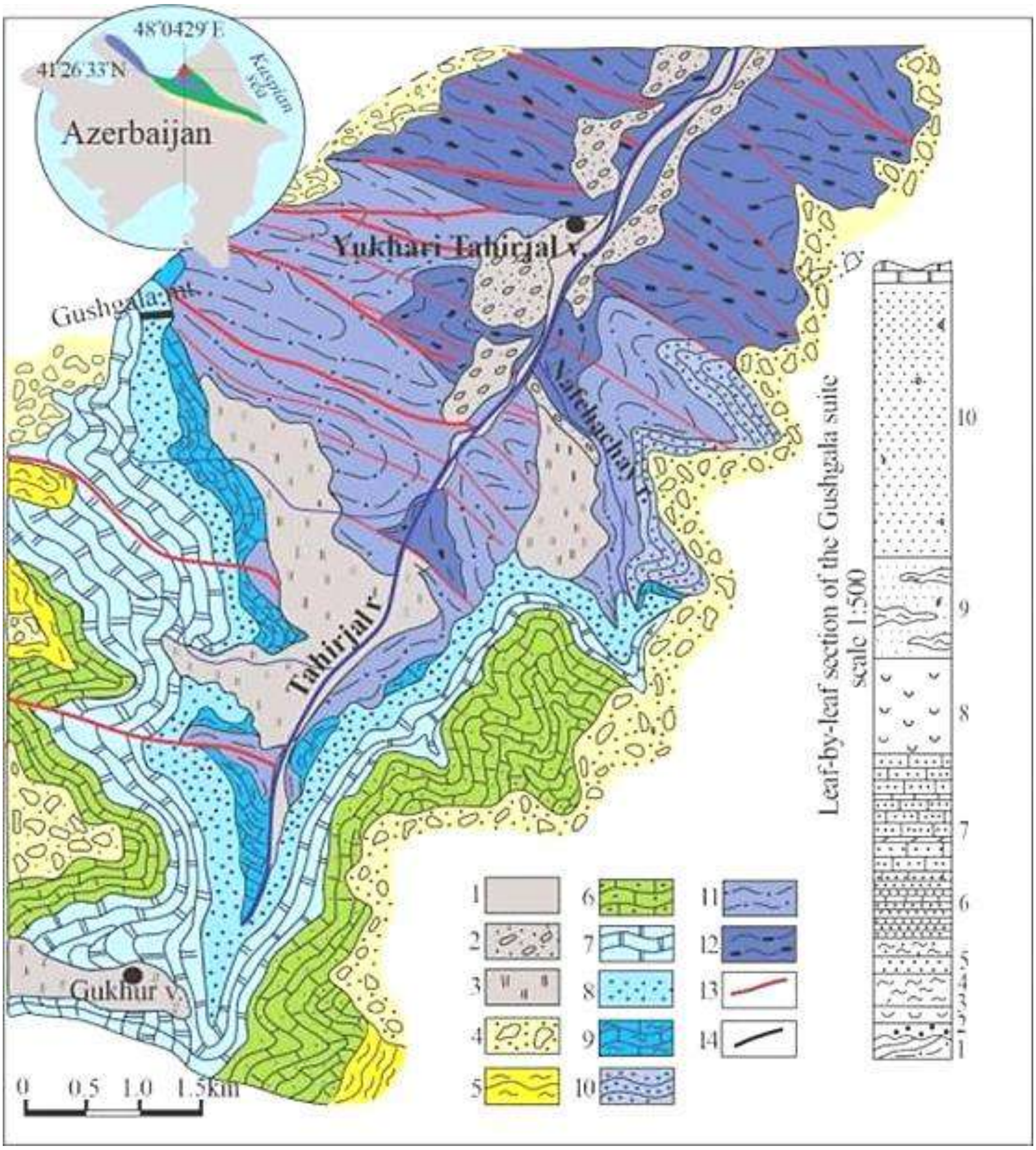


Fig. 1. Schematic geological map of the Tahirjalchay upstream basin compiled by T.N.Kangarli

1, 2, 3 – Holocene (channel deposits; deposits of river terraces; deluvial-colluvial deposits); **4** – Lower Pliocene: gravels and conglomerates with sandy-calcareous cement and lentiform interlayers of clays; **5** – Upper Miocene, Sarmatian Regional Stage; slate- gray clay with thick sand and sandstone layers; **6** – Neocomian: light gray siliceous, dolomite, oolitic and clastic limestone, Interbedded clayey sandstones; **7** – Kimmeridgian and Tithonian stages, Gukhur suite: pale yellow, pink and green-gray dolomite and limestone with rare intercalation sand lenses of clayey and calcareous sandstones; **8** – Lower Oxfordian, Gushgala suite: multicolored gypsum-bearing polymictic sands and sandstones with interlayers of glauconite clays, dolomites and basal conglomerates in the basement; **9** – Middle (?) Callovian – Lower Oxfordian, Tahirjal suite: Colorful sandy clay intercalated with light calcareous sandstone; **10** – Bajocian stage: grey massively bedded sandstones with interlayers of argillites; **11** – Upper Aalenian: alternating dark gray mudstone and sandstone, the latter predominating in the upper part; **12** – Lower Aalenian: dark gray clay, with siderite concretions and rare intercalations of sandstone on the horizon; **13** – rupture dislocations; **14** – location of taking the layer-by-layer section

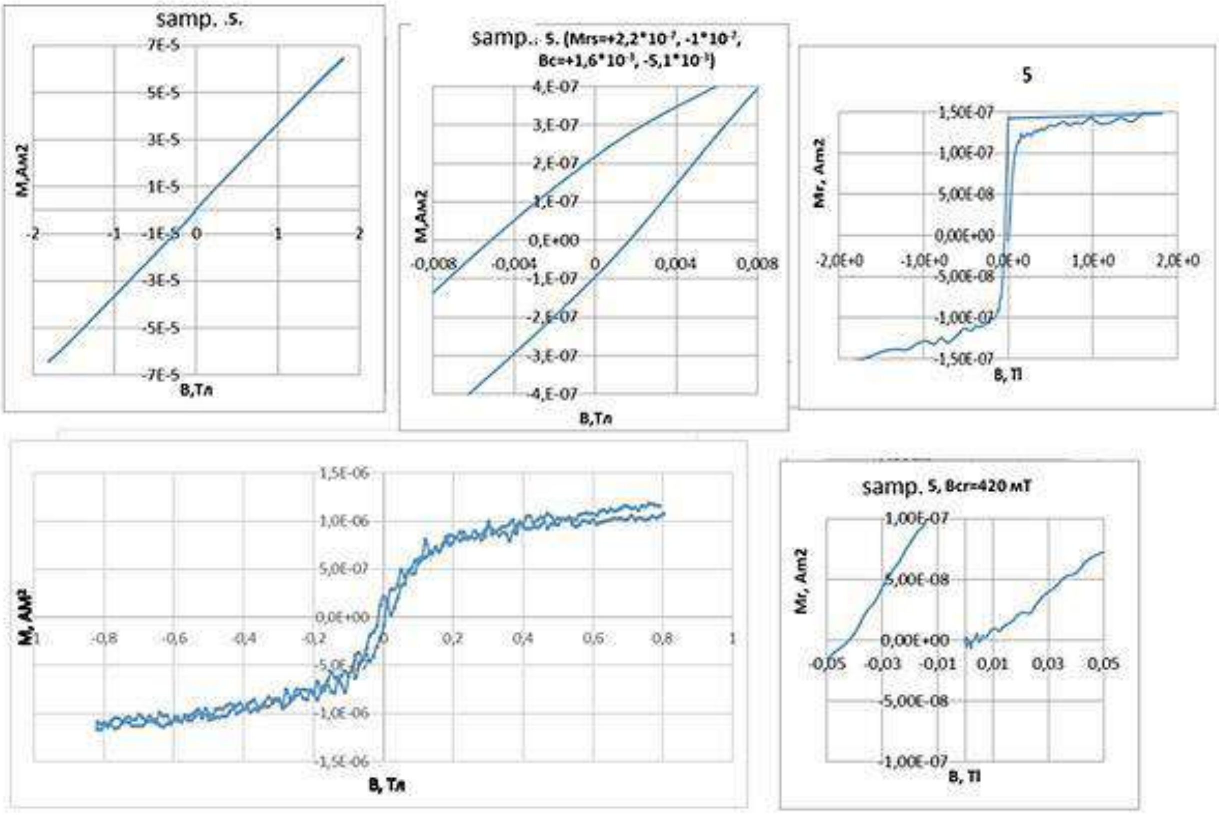


Fig. 2. Hysteresis loops (**a**) and its central part (**b**), after correction for the paramagnetic component (**c**), the curves of normal magnetization and "back-field" (**d**), sample 5

Alternating field demagnetization

The demagnetization of samples from the Tahirjalchay section by an alternating field was complicated by the fact that even with relatively small fields, regular magnetization occurred in the samples, probably associated with the presence of a large number of extremely soft magnetic grains, presumably having a size close to the super paramagnetic - single-domain threshold. In such samples, we can calculate the conditional characteristic component of magnetization, assuming that it begins to collapse, starting from fields of 5-10 mT. In some samples, however, cleaning continues successfully up to fields of 80 mT. In this case, sometimes, we can see clear indications of the presence of reverse polarity magnetization in the samples. According to the curves and stereograms obtained during alternating field demagnetization the studied rocks are divided into two groups. For the first group of rocks, it is demagnetized in fields varying from 200 mTl and retains about 20% of the initial value in fields of 400-450 mTl. Hysteresis parameters of the studied samples are given in Table 1.

Temperature demagnetization

The quality of the paleomagnetic signal in samples of this section is quite mediocre; at temperatures above 500-550°C, in most samples obvious magnetization occurs, expressed in a chaotic change in the magnitude and direction of magnetization. The natural residual magnetization in part of the samples includes two, and in part – three components of magnetization (Fig. 3).

The first, low-temperature component is probably a mixture of modern and laboratory viscous magnetizations. The second, medium-temperature component is destroyed in the temperature range from 200 to 500 or more degrees Celsius. The presence of this component, which does not go to the origin of coordinates, is obvious from Zijderveld diagrams (Fig. 3c) and magnetization reversal circles on stereograms (Fig. 3).

Table 1

Hysteresis parameters of the studied samples

Number of samples	Ms, mкAm^2	Mrs, mкAm^2	Mrs/Ms	Bc, mTl	Bcr, mTl	Bcr/Bc
3	56.7	0.151	0.003	1.9	37.4	19.7
	6.8	0.066	0.01	12	37.4	3.1
5	64.2	0.170	0.003	3.4	42.0	12.4
	7.6	0.154	0.02	8.2	42.0	5.1
13	60.0	0.092	0.002	0.472	37.0	78.6
	7.1	0.092	0.013	1.6	37.0	2.3
26	85.3	0.124	0.001	1.3	39.2	30.2
	9.8	0.121	0.012	8.4	39.2	4.7
27	61.4	0.068	0.001	1.1	38.3	34.8
	2.6	0.042	0.016	13.6	38.3	2.8
35	42.8	0.090	0.002	2.0	37.4	18.7
	0.99	0.110	0.12	12.2	37.4	3.1
53	30.3	0.111	0.004	3.3	43.4	31.2
	1.1	0.111	0.10	11	43.4	3.9
65	33.8	0.397	0.012	8.6	27.2	31.5
	1.4	0.397	0.27	54	27.0	5.0
72	74.8	0.108	0.001	2.3	38.4	16.7
	8.5	0.102	0.012	11.3	38.4	3.4
77	15.9	0.258	0.001	2.8	66.0	23.6
	8.1	0.58	0.29	10.6	18.5	10.4

The distribution of the characteristic component (after removing a certain number of outliers, which are probably the result of orientation or sawing errors) is shown in Fig. 3.

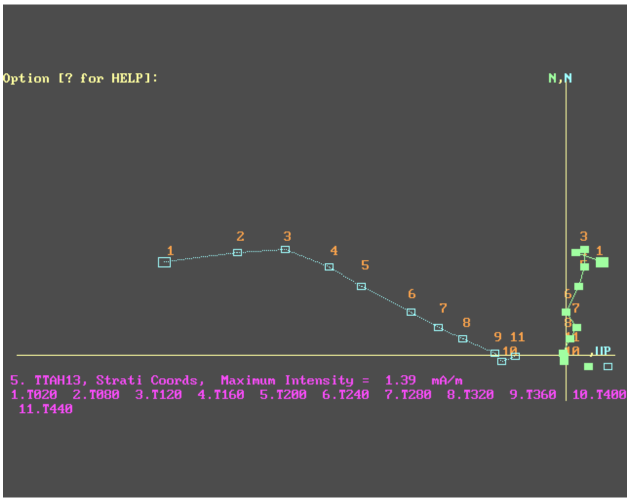
It is important to note that among the studied samples there are samples that carry magnetization of both direct and reverse polarity. After bringing the vectors to the same polarity, the fold test (Enkin, 2003) gives a positive result, indicating the pre-fold age of the identified characteristic component. This is also indicated by the fold straightening test, which shows the maximum distribution accuracy at 100% straightening.

The method of cleaning with temperature accurately separates the natural residual magnetization components. All samples are heated up to 600ºC. This process is carried out in steps every 30°C. After each heating, the samples are measured and reheated.

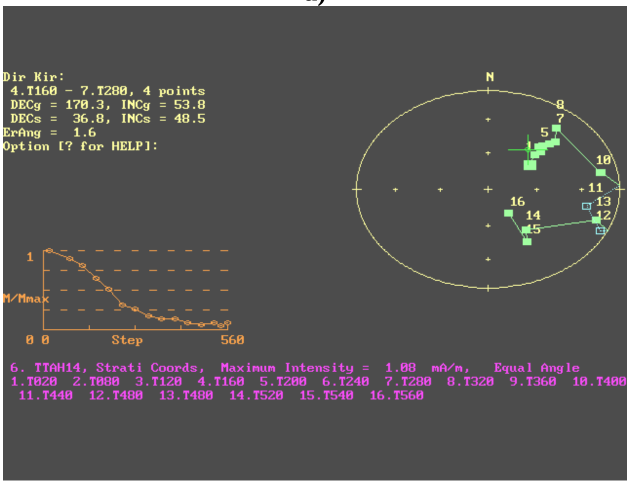
Depending on the temperature, the samples are divided into 2 groups according to the magnitude and direction of Jn.

Thus, the available data indicate that the characteristic magnetization identified in the Tahirjalchay section as a result of T-cleaning may be primary and reflect the direction of the geomagnetic field during rock formation. It should be noted that however, high inclination of the average direction of the selected characteristic component is surprising. According to the European apparent pole migration curve (Torsvik et al., 2012), the field inclination in the considered region should have been about 60°, the identified component has an inclination of about 80°.

The results of the demagnetization indicate that in a significant part of the rocks of the Tahirjalchay section, primary magnetization has been preserved and, in the future, these rocks can be used to solve various geological (including magnetostratigraphic) problems. In this case, the most promising method for isolating the primary (characteristic) component seems to be thermal magnetic cleaning. The primary magnetization appears to be noticeably contaminated by superimposed (secondary) magnetization components, therefore, successful isolation of the ancient component requires special efforts aimed, for example, as well as at the selection of the most suitable lithological varieties, the use of special procedures for magnetic cleaning, etc.



a)



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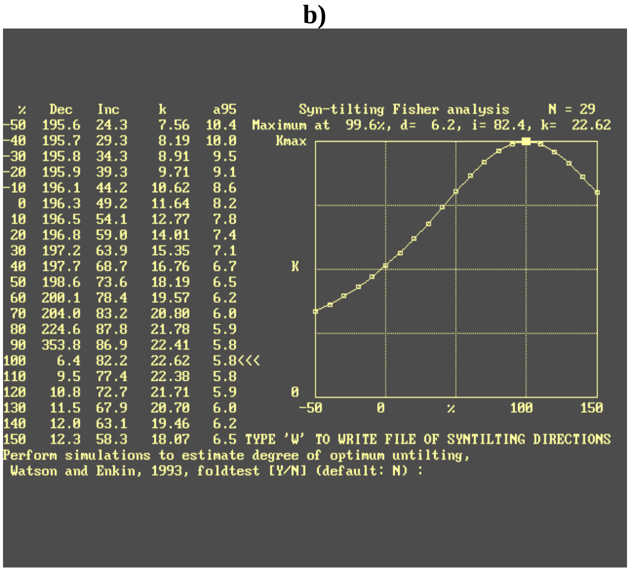

c)

Fig. 3. Zijderveld diagram of Tahirjalchay section (**a**), a stereogram illustrating the tendency of the EON vector to shift towards the expected direction of the primary magnetization of the reverse polarity (**b**). Distribution of vectors for a conditionally characteristic component, changes in the average directions and the corresponding Fisher parameters (accuracy *k* and radius of the 95% confidence circle α_{95}) during sequential "straightening of the fold" (**c**)

Thermomagnetic analysis

In thermomagnetic analysis, the samples are heated to 700°C. A single inflection point stands out on the curves $J_i(T)$, which is more clearly defined by the extremum of the second derivative and corresponds to the Curie point T=580ºC, which corresponds most likely to magnetite (Garayeva et al., 2023; Гараева и др., 2017; Novruzov et al., 2023; Новрузов и др., 2017). This result is consistent with the measurement data of hysteresis parameters. A common feature of all curves is that they reach a maximum at 500ºC to some extent. Typically, such peaks reflect the formation of new magnetic minerals upon heating. According to the temperature values, these peaks may be associated with the destruction of divalent iron contained in the clays and subsequent transformation into magnetite. In most of the studied sample magnetite is the main magnetic mineral-carrier of natural residual magnetization, in some cases hematite or iron hydroxides make a significant contribution to the total magnetization. To determine the natural residual magnetization, rock samples were subjected to both temperature and alternating magnetic cleaning (Fig. 4).

The first group of samples loses 50% of the initial magnetization at 120-175ºC. The stable part of J_n is observed at 300-350ºC. The second group of rocks loses 60-70% of its former temperature before heating to 150ºC. The stable part of I_n is observed in the range of 250-300ºC (Исаева и др., 2017).

Based on the magnetomineralogical studies conducted on the samples, the following can be said: their mean directions in the geographic coordinate system D=64º; J=31º; *k*=9; α_{95}=13º, mean direction in the stratigraphic coordinate system D=58º; J=71º; *k*=11; α_{95}=10º. The accuracy of the characteristic component is clearly improved by the 60% correction of the sedimentation layer (D=21º; J=71º; *k*=8; α_{95}=12º). Most of the studied samples have a component with an accuracy of 200 to 600 and higher, this component has a direction (in the Geographic coordinate system) close to the direction of the modern geomagnetic field; sometimes the calculated direction of this component cannot be compared with any possible direction either in the modern or in the ancient coordinate system (Исаева и др., 2016; Гараева и др., 2017; Novruzov et al., 2023).

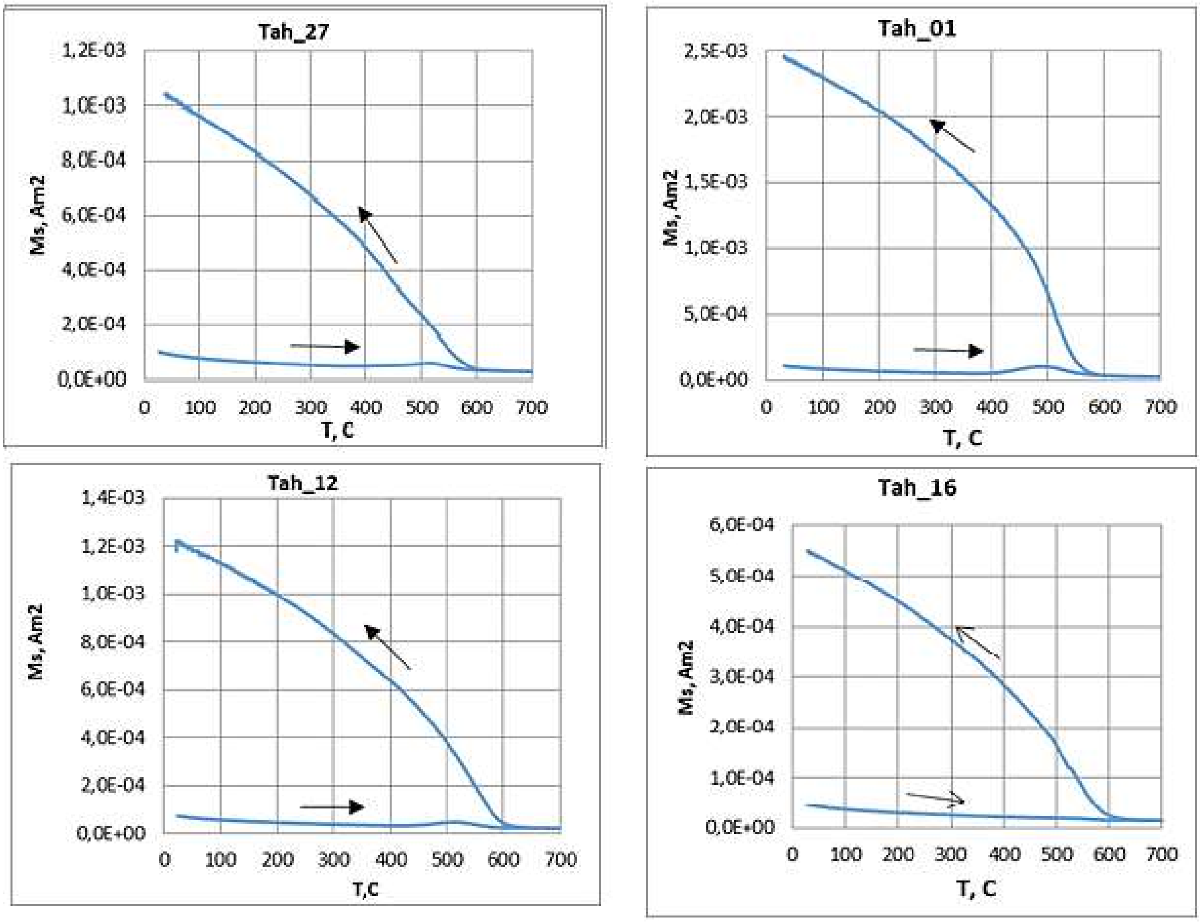

Fig. 4. Temperature dependence of saturation magnetization

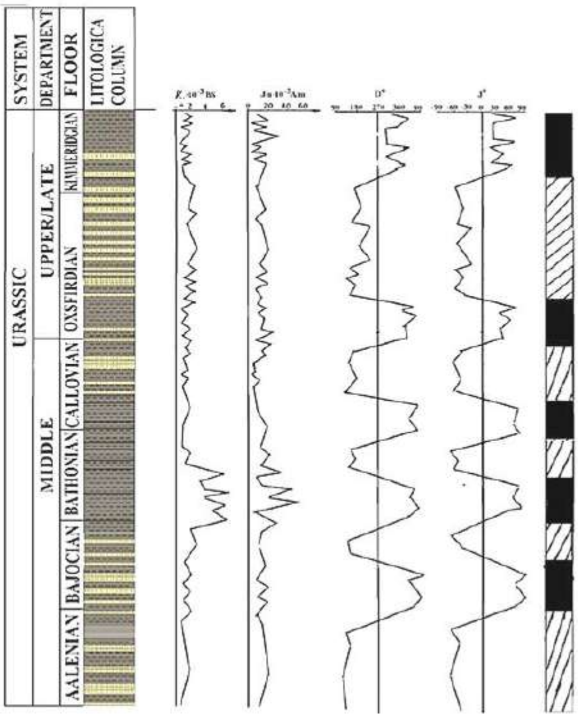

Fig. 5. Paleomagnetic column of the Tahirjalchay section

As a result of paleomagnetic studies, the paleomagnetic scale of the Middle and Upper Jurassic sediments of the Tahirjalchay section was compiled. A total of 5 direct magnetization zones and 5 reverse magnetization zones were detected (Fig. 5). Based on the detected 5 direct and 5 reverse magnetization zones, it is possible to give the exact boundary of all the stages.

Conclusions

- The comprehensive magnetomineralogical studies carried out made it possible to identify the carriers of residual magnetization in the composition of rocks, the Curie point, demagnetization of samples by a constant and varying magnetic field, etc. The magnetic properties of Jurassic sediments have been thoroughly studied, and it was found that they vary greatly in the natural residual magnetization and magnetic susceptibility. The reason for this variation in magnetic properties is the content of ferromagnetic minerals in their composition.
- The composition of the ferromagnetic fraction and the contribution of each magnetic mineral to the natural residual magnetiza-

tion were studied. Complex paleomagnetic research in the sediments of the Tahirjalchay outcrop, as well as, according to the nature of the curves of natural residual magnetization, it was confirmed that the magnetization carriers in the studied rocks are iron hydroxide, magnetite, and hematite.

- In the magnetostratigraphic scale established for the Tahirjalchay section, 5 direct and 5 reverse magnetization zones were detected, using these magnetic zones, the boundaries between stratigraphic stages were determined: Aalenian-Bajocian; Bajocian-Bathonian; Bathonian-Callovian; Callovian-Oxfordian; Oxfordian-Kimmeridgian. Based on paleomagnetic data, the kinematic parameters, rotations and horizontal displacements of the movement of the tectonic blocks of the Jurassic complex of the southern slope of the Scythian platform were studied for the first time.

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ПАЛЕОМАГНИТНЫЕ СВОЙСТВА ЮРСКОГО КОМПЛЕКСА СУДУРСКОЙ ШЕЛЬФОВОЙ ЗОНЫ БОЛЬШОГО КАВКАЗА (АЗЕРБАЙДЖАН)

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Резюме. В статье представлено детальное стратиграфическое деление юрского комплекса континентального шельфа Северо-Кавказского края Евразии. Стратиграфия юрских отложений региона, приуроченного к южной окраине Скифской платформы, до настоящего времени изучена недостаточно полно и требует уточнения. С другой стороны, палеомагнитные исследования в этой области ранее не проводились. Изучаемый район расположен на северном склоне юго-восточной части горно-складчатой системы Большого Кавказа. Для изучения палеомагнитных свойств юрских пород из разреза Тагирджалчай было отобрано 80 ориентированных образцов. Магнитная восприимчивость и естественная остаточная намагниченность отложений изменяются соответственно в пределах $0{,}6 \times 10^{-3} - 1{,}6 \times 10^{-3}$ BS и $2{,}9 \times 10^{-3} - 16{,}9 \times 10^{-3}$ А/м. Среднее значение постоянной компоненты указывает на то, что намагниченность близка к своему первоначальному состоянию и, следовательно, может быть использована для составления палеомагнитного профиля. На основе палеомагнитных данных впервые были изучены кинематические параметры юрских тектонических блоков на южной окраине Скифской платформы. Анализ исследовательских материалов выявил масштаб углового смещения блока. В результате магностратиграфического анализа разреза Тагирджалчай было выявлено всего 5 зон прямой намагниченности и 5 зон обратной намагниченности. Используя эти магнитные зоны, были определены границы между различными стратиграфическими подразделениями: аален–байос; байос–бат; бат–келловей; келловей–оксфорд; оксфорд–кимеридж.

Ключевые слова: *Тагирджалчайский разрез, магнитная чувствительность, остаточная намагниченность, палеомагнетизм, магнитная полярность*

BÖYÜK QAFQAZIN SUDUR ŞELF ZONASININ YURA KOMPLEKSİNİN PALEOMAQNİT XÜSUSİYYƏTLƏRİ (AZƏRBAYCAN)

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Xülasə. Məqalədə Avrasiyanın Şimal Qafqaz kənarının qitə şelfinin Yura kompleksi üçün detallı stratigrafik bölgü təqdim olunur. Skif platformasının cənub kənarına uyğun gələn bu ərazidə Yura süxur komplekslərinin stratigrafiyası kifayət qədər öyrənilməmişdir. Digər tərəfdən, bu regionda paleomaqnit tədqiqatları əvvəllər aparılmamışdır. Tədqiq edilən rayon Böyük Qafqaz dağ-qırışıqlıq sisteminin cənub-şərq hissəsinin şimal yamacında yerləşir. Yura süxurlarının paleomaqnit xüsusiyyətlərini öyrənmək məqsədilə Tahircalçay kəsilişindən 80 istiqamətləndirilmiş nümunə götürülmüşdür. Süxur nümunələrinin maqnit həssaslığı və təbii qalıcı maqnitləşməsi müvafiq olaraq $0,6 \times 10^{-3} - 1,6 \times 10^{-3}$ BS və $2,9 \times 10^{-3} - 16,9 \times 10^{-3}$ A/m intervalında dəyişir. Qalıcı komponentin orta dəyəri göstərir ki, maqnitləşmə ilkin vəziyyətinə yaxındır və buna görə də paleomaqnit profilinin tərtibində istifadə oluna bilər. Paleomaqnit məlumatları əsasında ilk dəfə Skif platformasının cənub kənarındakı Yura tektonik bloklarının kinematik parametrləri öyrənilmişdir. Tədqiqat materiallarının təhlili blokun bucaqlı yer dəyişməsinin miqyasını üzə çıxarmışdır. Tahircalçay kəsilişinin maqnostratigrafik təhlili nəticəsində cəmi 5 birbaşa maqnitləşmə zonası və 5 tərs maqnitləşmə zonası müəyyən edilmişdir. Bu maqnit zonalarından istifadə edilməklə müxtəlif stratiqrafik vahidlər arasında sərhədlər müəyyən edilmişdir: Aalen–Bajos, Bajos–Baton, Baton–Kellovey, Kellovey–Oksford, Oksford–Kimmeric.

Açar sözlər: *Tahircalçay kəsilişi, maqnit həssaslığı, qalıq maqnitləşmə, paleomaqnetizm, maqnit polyarlığı*